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MULTIWAVELENGTH LASER PROPAGATION STUDY

Final Report

July, 1972

J. Richard Kerr

Oregon Graduate Center
for Study and Research
19600 N.W. Walker Road
Beaverton, Oregon 97005
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13. ABSTRACT During the final semiannual reporting period, experiments were conducted on the effects of large (near-field) transmitter apertures, which under many circumstances have been theoretically predicted to result in a drastic reduction in scintillation. It was found that any such reduction requires highly-precise transmitter adjustments, and cannot be realized without some means of eliminating atmospherically-induced beam wander. In the presence of either strong turbulence or transmitter misadjustment, the beam at the receiver plane consists of a proliferation of transmitter-diffraction-scale spots, with large attendant scintillations. Further interpretation of the theory yields predictions of scintillation-reductions of practical importance for vertical links; however, fundamental doubts are expressed concerning the validity of the analyses. Also during the reporting period, a long-path field facility was established which will provide a very large integrated-path turbulence level, for detailed study of the statistics of saturated scintillations, and for the demonstration of saturation at the 10.6-micron wavelength. This facility will be utilized in a follow-on program.			

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SUMMARY

The purpose of this program is to experimentally investigate multi-wavelength laser beam scintillation phenomena over horizontal paths, and to relate these effects to the characteristics of atmospheric turbulence. Field experiments have been conducted with the use of specialized instrumentation which was developed on the program.

During the final semiannual reporting period, experiments were conducted on the effects of large (near-field) transmitter apertures, which under many conditions have been theoretically predicted to result in a drastic reduction in scintillation. It was found that any such reduction requires highly-precise transmitter adjustments, and cannot be realized without some means of eliminating atmospherically-induced beam wander. In the presence of either strong turbulence or transmitter misadjustment, the beam at the receiver plane consists of a proliferation of transmitter-diffraction-scale spots, with large attendant scintillations. Further interpretation of the published theory yields predictions of scintillation-reductions of practical importance for vertical links; however, fundamental doubts are expressed concerning the validity of these analyses.

Also during the reporting period, a long-path field facility was established which will provide a very large integrated-path turbulence level, for detailed study of the statistics of saturated scintillations, and for the

demonstration of saturation at the 10.6-micron wavelength. This facility will be utilized in the follow-on program which has been contracted with the Rome Air Development Center. Other future work will include the detailed investigation of the effects of turbulence intermittency on scintillation, and of techniques for eliminating beam wander.

The results of these efforts are applicable to target-illumination problems; to proposed transmitter diversity systems for alleviating such problems; and to receiver diversity approaches for image enhancement and improved performance of optical/infrared radar, reconnaissance, and communications systems.

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I. INTRODUCTION

The purpose of this program is to experimentally investigate multi-wavelength laser beam scintillation phenomena over horizontal paths, and to relate these effects to the characteristics of atmospheric turbulence. Field experiments have been conducted with the use of specialized instrumentation which has been extensively described in previous reports. The preceding semiannual report¹ contains a complete review of results through that period and requires no further discussion here.

The present report summarizes work performed during the final period of the contract, part of which is in preparation for a follow-on program.² Specifically, we discuss experimental transmitter-aperture effects on scintillations in Sec. II, and a new long-path field facility in Sec. III. In Sec. IV, a brief discussion of future work is given. Recent and currently-planned publications are listed in Sec. V, followed by references and figures in Secs. VI and VII respectively.

II. EXPERIMENTAL EFFECTS OF FINITE TRANSMITTER-APERTURES ON SCINTILLATIONS

In first-order scintillation theory³⁻⁸ it is predicted that variable laser-transmitter aperture-size and divergence or focus conditions will have a pronounced effect upon receiver signal fluctuations. In particular, a large reduction in scintillations is predicted for a collimated vertical beam or a horizontal beam focused on a near-field receiver. In the experiments

described below, we have studied this effect under conditions of weak and strong turbulence. The results, along with further interpretation of the theory, suggest serious deficiencies in the general understanding of transmitter effects on scintillation.

These deficiencies have important practical implications, especially in the design of earth-space laser systems, where the scintillation-reduction predicted for a collimated beam may be a critical factor in system design or feasibility. In this case, the turbulence effects are sufficiently weak that the first-order theory is always applicable. The predicted dependence on exact collimation adjustment, departure from beam-axis, and vertical turbulence profile are discussed below, where the criticality will be shown to be similar to that for the horizontal case detailed in Ref. 7.

A further practical aspect involves the degree to which finite transmitter apertures approximate point-sources in fundamental scintillation experiments.⁷

A. Theoretical Predictions

The expression for the on-axis log amplitude variance (σ^2) for a beam wave propagating over an arbitrary turbulence path is^{6,8}

$$\sigma^2 = 2.18 k^{7/6} L^{11/6} \int_0^1 C_n^2(x) f(x) dx, \quad (1)$$

where

$$f(x) = \text{Re} \left\{ \left(\frac{a_1 L (1-x)^2 + i (1-x) [(1-a_2 L)(1-a_2 Lx) + a_1^2 L^2 x]}{(1-a_2 L)^2 + (a_1 L)^2} \right)^{5/6} - \left(\frac{a_1 L (1-x)^2}{(1-a_2 L)^2 + (a_1 L)^2} \right)^{5/6} \right\}, \quad (2)$$

and k is the optical wavenumber, L is the path length, $C_n^2(x)$ is the refractive index structure constant, and $x = z/L$ is the normalized path-variable ($0 \leq x \leq 1$). The inverse transmitter-Fresnel-number³ is given by $a_1 L \sim \lambda L / D_T^2$, where D_T is the transmitter diameter; and $a_2 L = L/R$, where R is the radius of curvature of the outgoing wavefront. Values for $a_2 L$ of 1, 0 and < 0 represent focus, collimation, and divergence respectively.

In Eqs. (1,2) it is assumed that the Kolmogorov turbulence spectrum applies with a zero inner scale,⁹ and that the corresponding point-source scintillation is not saturated.¹⁰ The latter condition will be taken as the criterion for weak or moderate turbulence in the present discussion.

The reduction in scintillations is obviously related to the condition

$$a_1 L (1-x) \gg \left| (1-a_2 L)(1-a_2 Lx) + a_1^2 L^2 x \right|, \quad (3)$$

so that the two expressions in $f(x)$ nearly cancel. In the focused horizontal case,⁷ i.e. for constant C_n^2 , the near-field condition is $a_1 L \ll 1$ and approximate focus implies $(1-a_2 L) \approx 0$. The function $f(x)$ is then essentially zero except for

$$\frac{1-x}{x} \lesssim a_1 L, \quad (4a)$$

or

$$x \approx \frac{1}{a_1 L + 1} \approx 1 \quad (4b)$$

which implies that the scintillations originate near the receiver only. If we take x and $a_2 L$ as nearly unity, defocusing is negligible until $|1 - a_2 L| \gtrsim a_1 L$, which is equivalent to requiring that the geometric defocus angle be smaller than the diffraction angle. Physically, the condition on the transmitter focal adjustment is

$$\frac{\delta}{f} \ll a_1 L \frac{f}{L} \sim \frac{f\lambda}{D_T^2}, \quad (5)$$

where f is the focal length of the transmitter output mirror, and δ is the axial departure of this mirror from the point of geometrical focus on the receiver.

The predicted criticality of focus is thus severe, and the resonance-like curves of Ref. 7 show that small misadjustments may result in a very large enhancement of scintillations over that for a point source. The mechanism of this predicted enhancement is not clear; the experimental manifestations are discussed in Sec. II-C and the corresponding vertical case in Sec. II-F-1. We infer from this criticality that a non-diffraction-limited transmitter will not result in substantial scintillation reductions, contrary to the speculation of Refs. 5 and 11.

For a large, focused transmitter in a horizontal link, or for the collimated vertical case,⁵ the scintillation variance is proportional to $(a_1 L)^{7/6}$ or (transmitter area)^{7/6}. Surprisingly, this does not agree exactly with the $(\text{area})^{-1}$ dependence predicted from an angular-correlation viewpoint.¹²

As discussed below, a major deficiency in the theoretical development appears to be the neglect of atmospherically-induced beam wander. Physically, the on-axis position pertaining to Eq. (1) may be randomly steered off of a fixed receiver or target, and off-axis scintillations and beam-wander fades may be substantial. Analytically, larger (non-Kolmogorov) turbulence scales may be involved. The quantitative consideration of combined wander, spread, and scintillation effects is beyond the scope of this discussion.

B. Experimental System

The experiments were conducted at a 2m height over a 1.4 km path, using the 4880Å output of a stabilized argon laser. The general facility and instrumentation are fully described in Ref. 13.

The transmitter consisted of a 15 cm parabolic mirror and other optics, with an output gaussian beam size ($1/e^2$ irradiance points) which was variable from 0 to 15 cm. For smaller (0-5 cm) apertures, a 3.7 cm center obstruction was bypassed through off-axis illumination. Discrete settings of beam size (a_1) and wavefront curvature (a_2) were rapidly

obtained with mechanical stops on two moveable lenses. Spatial filtering was used at the input focus to the 15 cm parabolic mirror, with high resolution of the axial position of the pinhole. This permitted accurate focusing of the receiver plane as discussed below. The receiver size was variable from 3 mm to 32 cm, and the strength of turbulence was measured with a fast thermal microprobe.¹³

Measurements included log amplitude variance and covariance, probability distribution, and scintillation spectra. Qualitative features were studied photographically.

C. Qualitative Results

Under conditions of moderate turbulence for which the propagation theory is presumably applicable, the predicted reduction in receiver signal-fading for precise focusing was not observed. The physically obvious reason was atmospherically-induced beam wander occurring with time scales on the order of one $(\text{Hz})^{-1}$. In order to investigate the qualitative features of turbulence effects on finite beams, we used photographic techniques, the results of which will be discussed in this section.

For the case of a precisely focused near-field beam in moderate turbulence, a sequence of photographs (Figure 1) shows the existence of a non-evolving central spot which wanders but apparently does not scintillate appreciably. The spot is equal in size to the diffraction scale of the transmitter, and the pattern outside of this region evolves constantly.

The effect of slight defocusing is shown in Figure 2, where each successive frame represents an axial motion of the pinhole of 50 μm compared to an output focal length of 120 cm ($\delta/f = 4.2 \times 10^{-5}$). This may be compared to the quantity λ/D_T^2 (Eq. 5), which is 2.6×10^{-5} and is thus comparable.

It is apparent that a minor degree of defocusing eliminates the behavior illustrated in Figure 1, and results in an evolving (scintillating) pattern which is broken-up into several diffraction-scale spots. This may represent the enhancement of scintillation predicted by the theory; such enhancement has also been measured in wind tunnel experiments.¹⁴ Hence a criticality is indeed manifested, and the scintillation theory (Eq. 1) may be meaningful for a point which is moving with the centroid of the wandering beam. An accurate test of this hypothesis would require a scanning or arrayed receiver, or the use of an active wander-cancellation scheme such as that suggested by a recent theory of reciprocity.¹⁵

It may be noted that locating and maintaining the precise focus condition presents major practical difficulties for real operating systems. Also, the scintillation-reduction at focus predicted by Eq. 1 does not apply off of the instantaneous centroid, and it is apparent from Figure 1 that scintillations may be quite severe for points at off-axis radii of one diffraction scale or more.¹⁶

Under conditions of strong turbulence, the focused spot is broken up into a proliferation of evolving, transmitter-diffraction-scale

patches (Figure 3). Under these conditions, for which the theory is applicable, the wavefront distortion is such that focusing loses its meaning, and beam spread predominates over beam wander.

It may be noted that the truncation and occultation of the gaussian laser beam does not give rise to discernible diffraction rings. It is believed that the use of a uniformly-illuminated transmitter aperture would result in the same general behavior as shown in Figs. 1-3; e.g. for moderate turbulence and accurate focusing, the centroid would not evolve or scintillate, although details outside this region would involve diffraction rings.

D. Quantitative Results - Variance and Covariance

The log amplitude variance, normalized by the simultaneous value for a point source and receiver, is shown for various transmitter and receiver conditions in Figure 4. The bars indicate the range of results obtained in a number of measurements, all at times for which σ_s^2 was unsaturated. The first result illustrates the equivalent point-source scintillation behavior of a large, divergent beam as predicted by theory (Ref. 7). The second result, which represents accurate focusing on the receiver, shows severe fading due to wander, and hence does not evidence the pronounced scintillation-reduction predicted by Eq. (1). The third result represents an attempt to capture all of the focused energy in a large receiver, but beam wander is still sufficient to result in some fading. The fourth is for a small

receiver and transmitter and is unity by definition; the final result indicates aperture-smoothing of a point source by a large receiver.¹³

Similar measurements for strong turbulence conditions (σ_s^2 saturated) are shown in Figure 5. A large, divergent beam scintillated somewhat less than a point source, in agreement with the trend shown in Russian data.¹⁰ The geometrically focused beam was substantially spread by the atmosphere (Figure 3), with scintillation behavior which was indistinguishable from that for the divergent source of the same size. This is as expected, since atmospheric wavefront distortion predominated and the original transmitter-wavefront curvature was immaterial. With spread predominating over wander, the signal fading for the same beam with a large receiver was greatly reduced; due to the presence of small (transmitter diffraction) correlation scales, the smoothing was better than that for the point source case in either strong or weak turbulence. The results for an intermediate-size transmitter are also shown in Figure 5, including diverged and focused beams and a large receiver. Finally, the degree of aperture smoothing for a point source and large receiver showed much spread and was often smaller than for weaker turbulence.¹³

Typical log amplitude covariance results for strong turbulence conditions are shown in Figure 6. The diffraction scale of the large transmitter (0.9 cm) is evident for the focused case but not for the divergent case. The curve for the point source has a long tail as observed elsewhere.^{10,13} The corresponding $1/e$ separations for a number of covariance measurements

in strong turbulence are shown in Figure 7 and, except for the focused case, indicate long tails with large variability.

Covariance results for weaker turbulence conditions are shown in Figure 8. In this case, the diffraction scale of the focused beam is obliterated by beam wander, and the divergent and point-source beams result in smaller tails than for strong turbulence.

E. Scintillation Spectra and Probability Distributions

Receiver aperture smoothing has been theoretically predicted to result in a reduction in the higher-frequency components of scintillation.¹⁷ The effects of finite beam waves on scintillation spectra have been only briefly analyzed.⁸ Although certain investigators have failed to find receiver¹⁸ or receiver and transmitter¹⁹ aperture spectral effects, there are a number of observations of receiver smoothing of high frequency components.^{10,20}

Scintillation spectral width measurements, determined as in Ref. 13, are shown for moderate turbulence in Figure 9. Higher-frequency components were evidently suppressed for either finite receiver or (focused) transmitter apertures, and especially for both. Spectral components related to beam wander were much lower than those due to scintillation, and do not affect these measurements. Similar measurements for high turbulence (Figure 10) again indicate the inapplicability of concepts such as "focusing" for this case; the high-frequency suppression is apparently related to receiver smoothing only.

Log amplitude probability distributions for point sources and finite receiver apertures were log normal in accordance with predictions by Mitchell.²¹ An example of good log normality is shown in Figure 11, including the case of a near-field, focused beam. However, beam wander often resulted in distorted distributions, as shown in Figure 12. The statistics for such cases depends upon the exact position of the beam relative to the long-term centroid, and the relative strength of wander - vs scintillation-induced fading.

F. Other Aspects

1. Vertical Paths

For the case of a collimated, vertical beam, Fried⁵ has predicted a reduction in scintillation which is comparable to the horizontal prediction for a focused beam. An exponential fall-off of turbulence with altitude is assumed. For reasonable zenith angles, the theory should not be invalidated by strong turbulence, and since the receiver is usually postulated to be in the far field of the transmitter, beam wander is no longer a factor. In view of the horizontal considerations discussed above, it is of interest to consider the possible criticality of the collimation adjustment, and the sensitivity of the scintillation reduction to the actual vertical turbulence profile--including the possibility of significant contributions from the tropopause.

If we neglect the possible effects of the inner scale, we may examine the above factors by inspection of Eqs. 1-3. For the earth-to-space case, $\alpha_1 L \gg 1$, and near-collimation is indicated by $\alpha_2 L \approx 0$. For perfect collimation, the condition (3) becomes

$$\frac{1-x}{x} \gg \frac{1}{\alpha_1 L x} + \alpha_1 L. \quad (6a)$$

Since $\alpha_1 L \gg 1$, this immediately becomes

$$x = \frac{z}{L} \ll 1/\alpha_1 L \sim \frac{D_T^2}{\lambda L}. \quad (6b)$$

Hence, the scintillation reduction will be achieved as long as the turbulence or weighting function $C_n^2(x)$ is significant only in the near field of the transmitter.

For perfect collimation, the scintillation reduction vs α_1 (or D_T) is expected to be similar to that for the horizontal case since the same terms $(1-\alpha_2 L)$ become unimportant in Eq. (2). This agrees with the results of Refs. 4 and 5.

In order to examine the effects of imperfect collimation, we note that the near-field requirement on $C_n^2(x)$ combined with the far-field assumption on the range L permits us to assume $x \ll 1$ for nonzero turbulence.

Let us first consider a divergent beam ($\alpha_2 L < 0$). Using $x \ll 1 \ll \alpha_1 L$ and (6b), condition (3) becomes

$$|\alpha_2 L| \ll \alpha_1 L. \quad (7)$$

Physically, the distance defined by the parameter $|R|$ must be in the far field of D_T , although it may be less than L . The criticality of adjustment is again given by Eq. (5): the geometrical spread must be less than that owing to diffraction. For further departures from collimation, a large scintillation-enhancement is again predicted.²²

For a converging beam ($\alpha_2 L > 0$), a term-by-term consideration of Eq. (3) again yields (7), but there exists an apparent possibility of a further reduction in scintillations. This possibility is closely related to a suggestion by Titterton,²² and includes the prediction of a total cancellation of scintillations from a thin layer of turbulence, e.g. at the ground or even the tropopause.

Let us assume that the layer is located at $x = x_0$, and set the RHS of Eq. (3) to zero, thus making $f(x)$ vanish in Eq. (2). The solution for α_2 is

$$\alpha_2 = \frac{1}{R} = \frac{(1+x_0) \pm \left((1-x_0)^2 - 4 x_0^2 \alpha_1^2 L^2 \right)^{1/2}}{2 L x_0} . \quad (8)$$

The solution is real if

$$(1-x_0) \geq 2 x_0 \alpha_1 L = 2 \alpha_1 z_0 , \quad (9)$$

which states that $2z_0$ must be in the near field of the transmitter, and increasingly-so as $x_0 \rightarrow 1$. We note that $R > z_0$.

If we represent ground-layer and tropopausal turbulence by

$$C_n^2(x) = A\delta(x) + B\delta(x-x'), \quad (10)$$

where x' is the tropopause height and A, B are constants, then an optimum value of α_2 or R may be found from Eq. (1).

2. Reciprocity

As a consequence of recent results from a straightforward theory of reciprocity for propagation through turbulence,²³ the basic correctness--or at least the realm of validity--of the beam wave scintillation analyses must be considered questionable. For example, let us consider a focused horizontal link and the conceptual reciprocal system in which a point on the receiver plane becomes a signal source for optical heterodyne detection by the transmitter optics. It is well known²⁴⁻²⁶ that as the aperture is enlarged beyond a critical size r_0 , the heterodyne signal will become independent of the aperture and the modulation noise due to wavefront distortion will increasingly degrade overall performance. However, in the corresponding nonreciprocal case, as D_T is increased the beam wave theory predicts a continual and unlimited reduction in scintillation.

Beam wander--or the reciprocal image dancing--does not provide an adequate explanation of this contradiction. For $D_T > r_0$, reciprocity suggests that the transmitted beam will be primarily spread and broken-up, and hence scintillating. The condition on path length and turbulence

$(C_n^2 L)$ for this to occur is more severe as D_T is increased:

$$r_o^{4/3} = \frac{2.4}{C_n^2 L k^2} \geq D_T^{5/3} \quad (11a)$$

or

$$C_n^2 L \leq \frac{2.4}{k^2 D_T^{5/3}} \quad (11b)$$

This may also be written

$$\sigma_s^2 = 0.124 C_n^2 L^{1/6} k^{7/6} \leq (\text{constant}) \times (a_1 L)^{2/5} \quad (12)$$

For a fixed Fresnel number, the condition is functionally identical to that for the saturation of σ_s^2 or the breakdown of the basic first-order theory for plane or spherical waves. However, for useful (i.e. near-field) apertures, it is much more stringent numerically. It is suggested that the beam wave results involve a hitherto unrecognized condition on validity which is transmitter-aperture dependent and generally stricter than that for simple sources. The same general conclusion would also apply to the vertical case.

Finally, we note that the condition (12), when combined with the asymptotic dependence $\sigma^2/\sigma_s^2 \sim (a_1 L)^{7/6}$, suggests that the maximum achievable transmitter smoothing of scintillations under given conditions is $\sigma^2/\sigma_s^2 \sim \sigma_s^{-14/5}$.

G. Summary

In summary, the beam wave turbulence propagation theory which predicts substantial reductions in scintillations under certain conditions has been shown to inadequately account for fading due to beam wander effects, and more seriously, is questioned as apparently contradicting the results of a simple theory of reciprocity. This contradiction may be resolved through a condition on validity which is dependent upon transmitter size, strength of turbulence, and path length. It predicts a high degree of criticality in focusing or collimation, and we have shown experimental evidence that such criticality has real physical manifestations; specifically, for moderate turbulence and precise focusing, a wandering beam centroid with low scintillation can be observed. However, for a slightly misadjusted transmitter, or for strong turbulence, the beam at the receiver plane consists of a proliferation of transmitter-diffraction-scale spots.

To the extent that the theory has validity, there exists the possibility of achieving low scintillations over a horizontal path through active cancellation of beam wander, and over a vertical path through collimating or even converging the beam to minimize effects from a thin turbulent layer such as that at the tropopause.

III. NEW LONG-PATH FIELD FACILITY

A new field facility has been established which will provide a flat, four-mile propagation path with a very high integrated-path turbulence (Figure 13). The facility will be utilized in the follow-on program for the determination of parameter dependencies and scintillation statistics at 4880Å and 10.6-micron wavelengths for this extreme case. The results should include the demonstration of saturation at 10.6 microns, and very strong "supersaturation" at 4880Å. The effort will include the measurement of covariances, probability distributions, scintillation spectra, and receiver aperture-averaging.

A major problem with such a long, high-turbulence path is the large and variable beam-refraction in the vertical plane. This effect causes the laser beams to curve upward significantly and to a degree which has both short- and long-term variations. The short term (beam wander) effect is negligible due to the large beam-divergence. The long-term effect essentially raises the virtual horizon and necessitates increasing the beam height at each end of the path while pointing it down somewhat (Figure 14). The desired optical path is one which comes within e.g. one meter of the ground cover at midpath; maintaining this condition requires changes in the transmitter height of up to several meters over a diurnal period.

The transmitter shack is shown in Figure 15. The tower contains a twenty-foot-high steel structure which is isolated from the shack and

sunk into a massive concrete base. This tower, with associated output ports, permits changing the output beam height in two-foot increments, simply by moving one mirror and the BaF1 output window (Figure 16). Such a change requires only a few minutes. The appropriate height at any given time is determined with a portable sighting telescope.

The transmitter consists of stable, low-noise Ar and CO₂ lasers and associated optics for obtaining coincident beams which represent virtual point-sources. As in earlier phases of the program, this is done in order to obtain unambiguous, spherical-wave results. The inverse Fresnel number (a_1L) is on the order of 10^3 for the visible beam and 600 for the infrared. The corresponding sizes at the receiver plane are two and eight meters respectively. Initial experiments indicate that further divergence may be necessary at the visible wavelength, in order to completely cancel wander effects.

The lasers and optics are mounted on a concrete base (Figure 17). The optical arrangement is indicated in Figure 18. Initial beam steering is accomplished at 4880Å through use of the coaxial sighting telescope and precision mirror-rotators, including a remote-control unit on the tower-mounted output mirror. The infrared beam is then made precisely coaxial with the visible beam. This procedure assumes that the atmospheric refraction will be substantially the same at both wavelengths--an assumption which has proven correct.

The steering technique is consistently successful and results in rapid signal acquisition. The centering of the infrared beam on the receiver may be checked by slow dithering in the horizontal and vertical planes respectively, while monitoring the average signal level. This procedure has shown that the basic pointing method is quite sufficient. Once the coaxial condition is established, any restearing necessitated by changing atmospheric conditions is accomplished using those mirrors which affect both the visible and infrared beams in an identical manner; hence further pointing problems with the infrared beam are circumvented.

The receiver optics and electronics are as described in previous reports on this program, and include both dual-point and large-aperture receivers for the two wavelengths, with specially-designed, real-time analog recording and data processing instrumentation. The receiver height is approximately three meters. The turbulence level is monitored with a fast, sensitive thermal microprobe as described previously. Communication between the shacks is provided by telephone, and automatic alarm systems notify police in case of attempts at theft or vandalism.

Initial experiments show that the link works quite successfully, but that variable-height flexibility is desirable on the receiver end also. This will be provided by a simple periscope.

IV. FUTURE WORK

In addition to the long-path measurements, the efforts in the follow-on program will include the demonstration of a beam-wander-cancellation technique related to the reciprocity considerations discussed in Section II, and the detailed investigation of the effects on scintillations of the fundamental intermittency of atmospheric turbulence.

V. CURRENT PUBLICATIONS

During the semiannual reporting period, the following papers have been presented, published, or accepted for publication:

1. J. R. Kerr and R. Eiss, "Transmitter-Size and Focus Effects on Scintillations," JOSA 62, May 1972, pp. 682-684.
2. J. R. Kerr and J.R. Dunphy, "Transmitter-Aperture Effects on Laser Scintillation," Paper WE17, 1972 Spring Meeting, Optical Society of America, New York, N.Y., April 11-13, 1972.
3. J. R. Kerr, "Comments on 'Irradiance Fluctuations in Optical Transmission through the Atmosphere,' " JOSA 62, July 1972, p. 916.
4. J. R. Kerr, "Experiments on Turbulence Characteristics and Multiwavelength Scintillation Phenomena," to be published in JOSA, September, 1972.

In addition, Section II of this report comprises a preprint which will be submitted to JOSA.

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VII. LIST OF FIGURES

1. Characteristic received beam for a focused, near-field transmitter ($\alpha_1 L = 0.09$) in moderate turbulence. The duration of each frame was 4 msec and the time between adjacent frames was 21 msec. The scale marks represent 2.5 cm.
2. Received beam vs transmitter focal adjustment for a near-field transmitter in moderate turbulence. Successive frames represent axial focal adjustments of 50 μm out of an effective focal length of 120 cm. Precise focus is illustrated in the third frame. Individual patches are the same nominal size as the central spot in Figure 1.
3. Received beam for a focused, near-field transmitter in strong turbulence. Individual patches are the same nominal size as the central spot in Figure 1.
4. Normalized log amplitude variance for moderate turbulence vs transmitter and receiver diameter and transmitter divergence. The bars and circles respectively indicate the range and average of a number of results obtained on different days. Each measurement is normalized by the simultaneous variance for a virtual point source and receiver. The large and small transmitter apertures correspond to ($\alpha_1 L = 0.90, 320$) respectively, while a diverging and focused beam corresponds to ($\alpha_2 L = 10, 1.0$). The receiver diameter is denoted by R_x .
5. Measurements similar to those of Figure 4, for strong turbulence.
6. Typical log amplitude covariance curves for strong turbulence. The circles indicated the $1/e$ ordinate points.
 - a. Large, focused beam ($\alpha_1 L = 0.09, \alpha_2 L = 1.0$)
 - b. Large, diverged beam ($\alpha_1 L = 0.09, \alpha_2 L = -10$)
 - c. Virtual point source ($\alpha_1 L = 320$)
7. $1/e$ covariance separations (r_a) vs transmitter conditions for a series of measurements of the type illustrated in Figure 6. The bars and circles respectively indicate the range and average of a number of results obtained on different days.
8. Measurements similar to those of Figure 6, for moderate turbulence.

9. Scintillation spectral widths (Ref. 13) for moderate turbulence vs transmitter and receiver conditions. The bars and circles respectively indicate the range and average of a number of results obtained on different days. Each measurement is normalized by the simultaneous spectral width for a virtual point source and receiver.
10. Measurements similar to those of Figure 9, for strong turbulence.
11. Cumulative probability distributions vs transmitter and receiver conditions. These examples indicate good log normality.
 - a. Large, focused beam ($\alpha_1 L = 0.09$, $\alpha_2 L = 1.0$)
Large receiver (Diameter $R_x = 30$ cm).
Abcissa: 0.1 dB of photocurrent per division
 - b. Large, focused beam ($\alpha_1 L = 0.09$, $\alpha_2 L = 1.0$)
Small receiver ($R_x = 0.3$ cm)
Abcissa: 10 dB of photocurrent per division
 - c. Virtual point source ($\alpha_1 L = 320$)
Small receiver ($R_x = 0.3$ cm)
Abcissa: 10 dB per division
 - d. Virtual point source ($\alpha_1 L = 320$)
Large receiver ($R_x = 30$ cm)
Abcissa: 0.1 dB of photocurrent per division
12. Cumulative probability distributions for a large, focused beam ($\alpha_1 L = 0.09$, $\alpha_2 L = 1.0$) under conditions of predominant beam wander. The wander causes significant departures from log normality.
 - a. Small receiver ($R_x = 0.3$ cm)
Abcissa: 10 dB of photocurrent per division
 - b. Large receiver ($R_x = 30$ cm)
Abcissa: 0.1 dB of photocurrent per division
13. View of four-mile path from transmitter site.
14. Illustration of atmospheric beam-refraction effect.
15. View of transmitter shack at long-path facility.

16. Schematic diagram of tower arrangement for changing transmitter beam-height.
17. Transmitter lasers and optics
18. Transmitter optical system

FIGURE 1

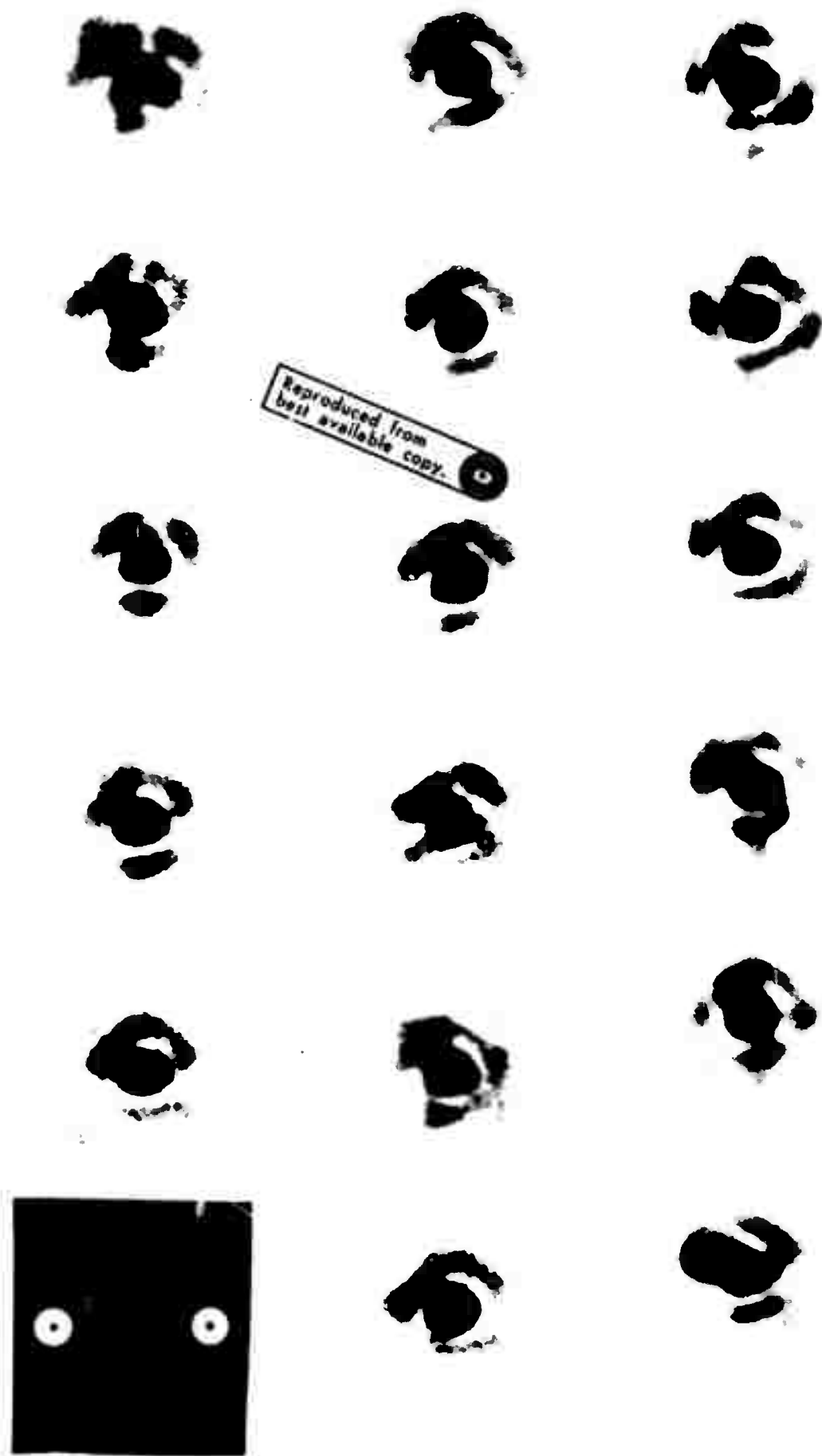


FIGURE 2

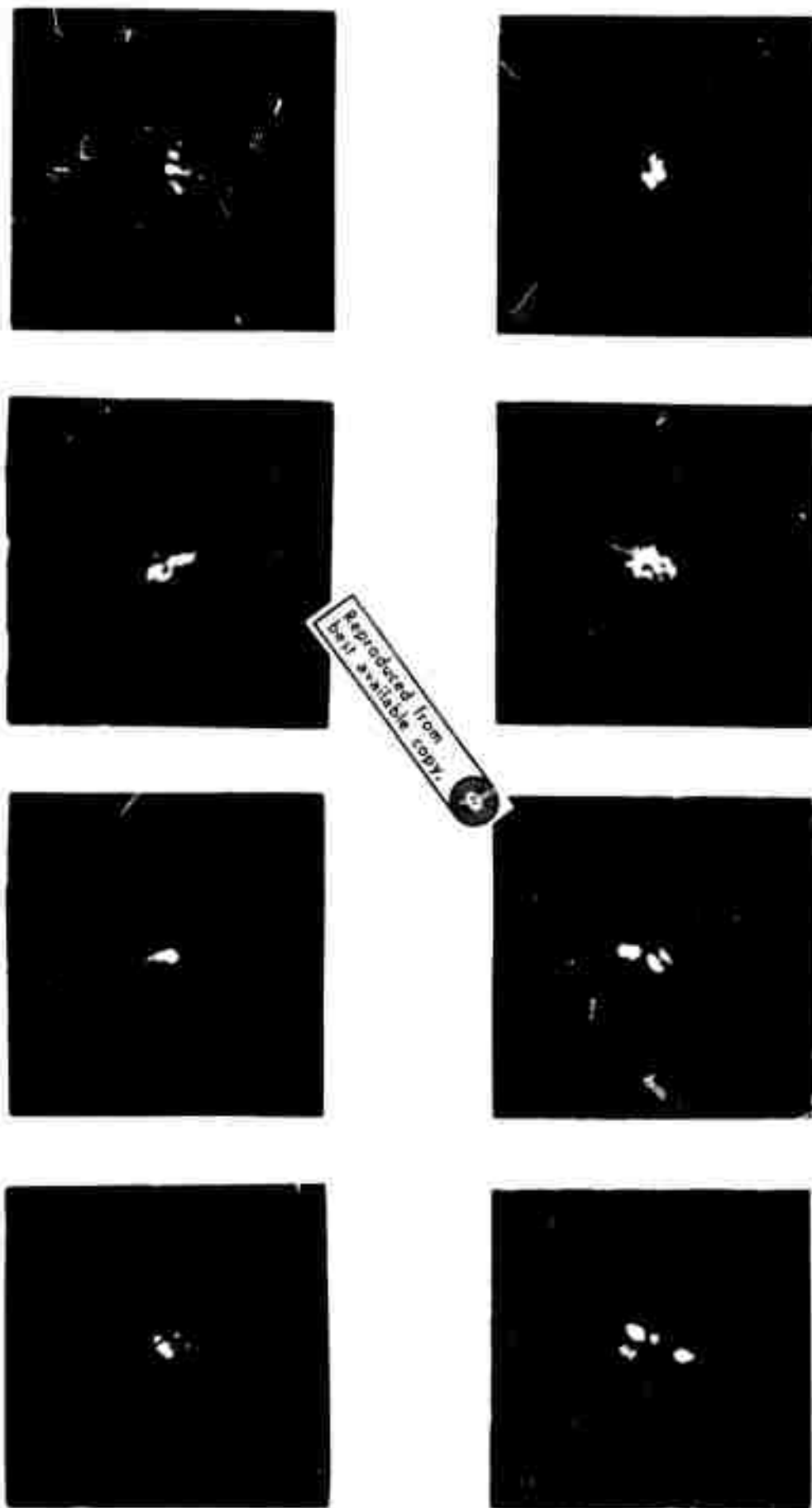


FIGURE 3



FIGURE 4

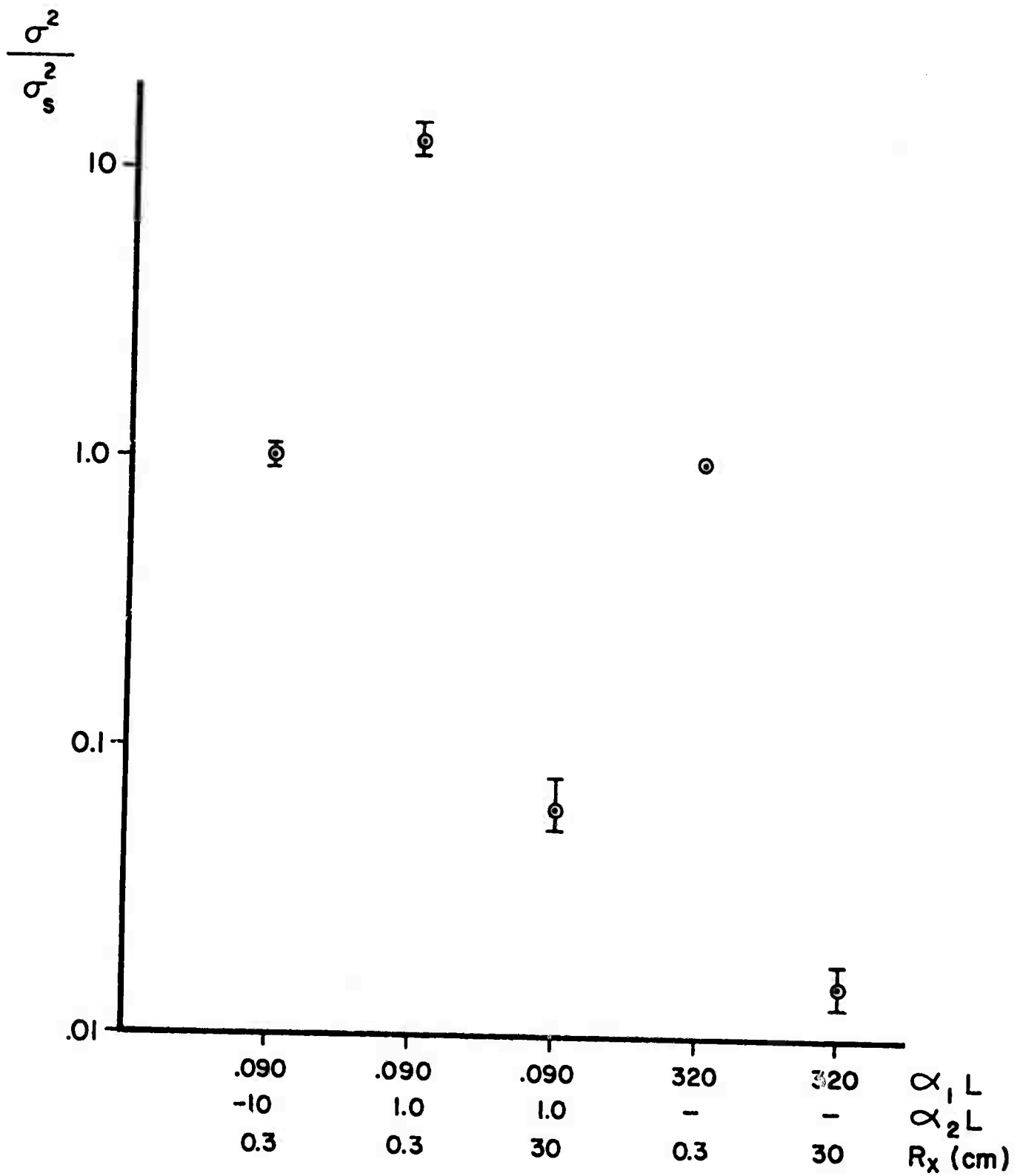


FIGURE 5

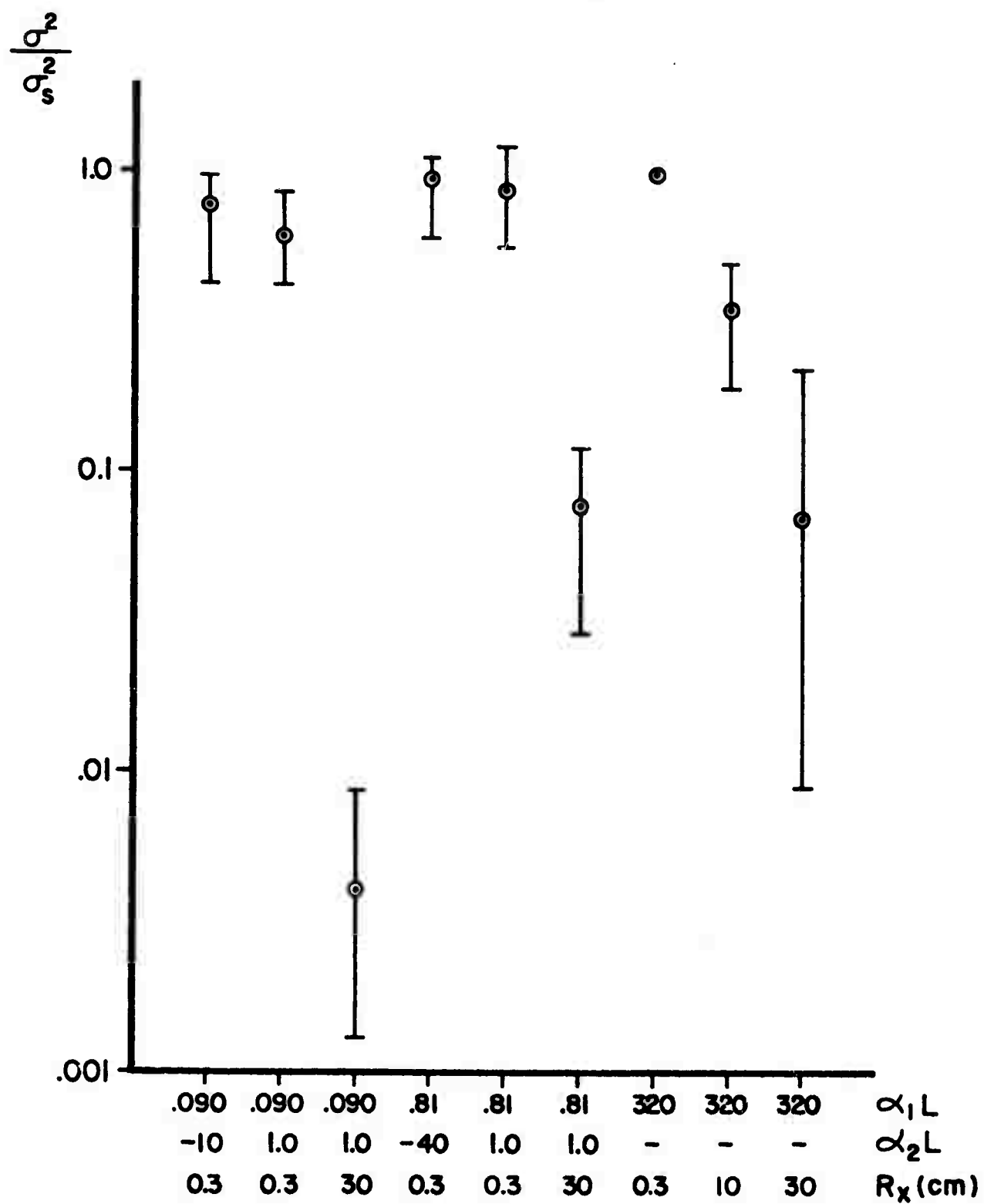
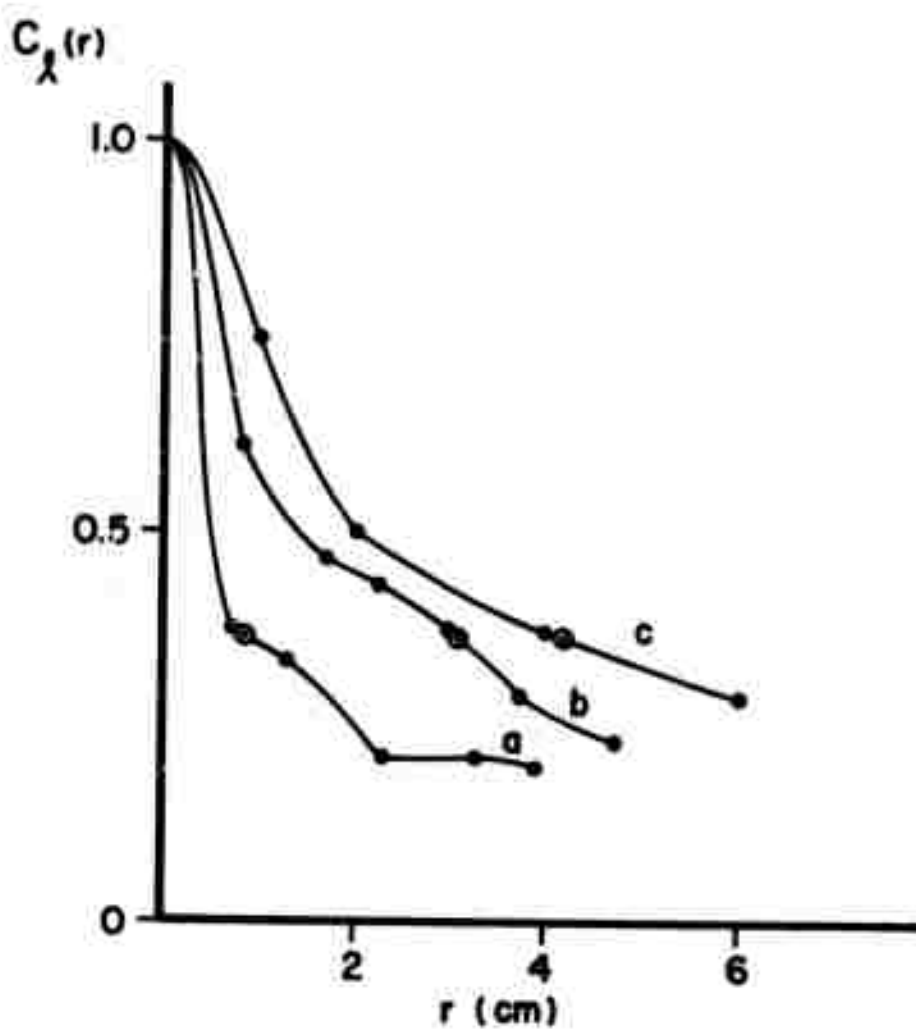


FIGURE 6



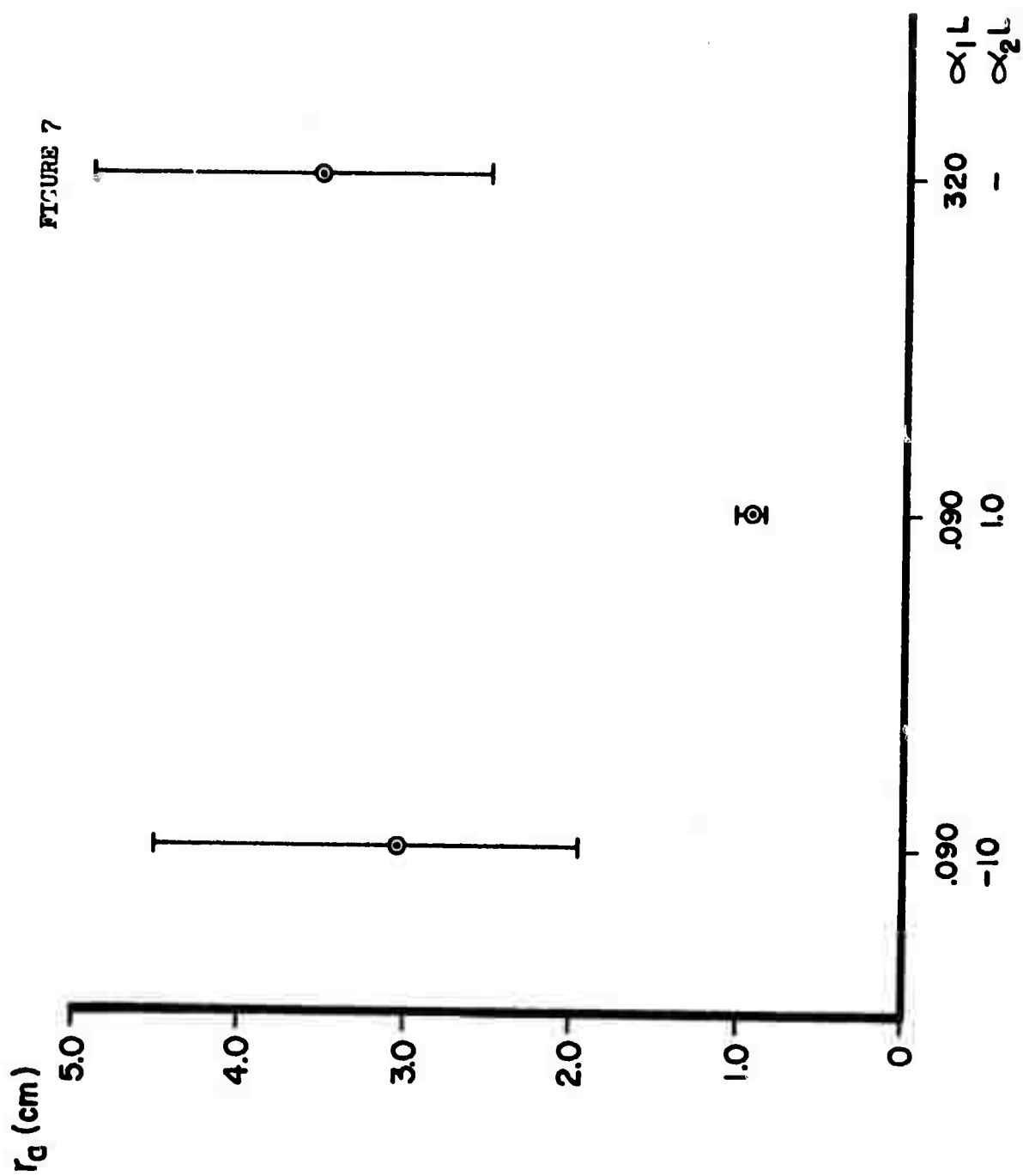


FIGURE 7

FIGURE 8

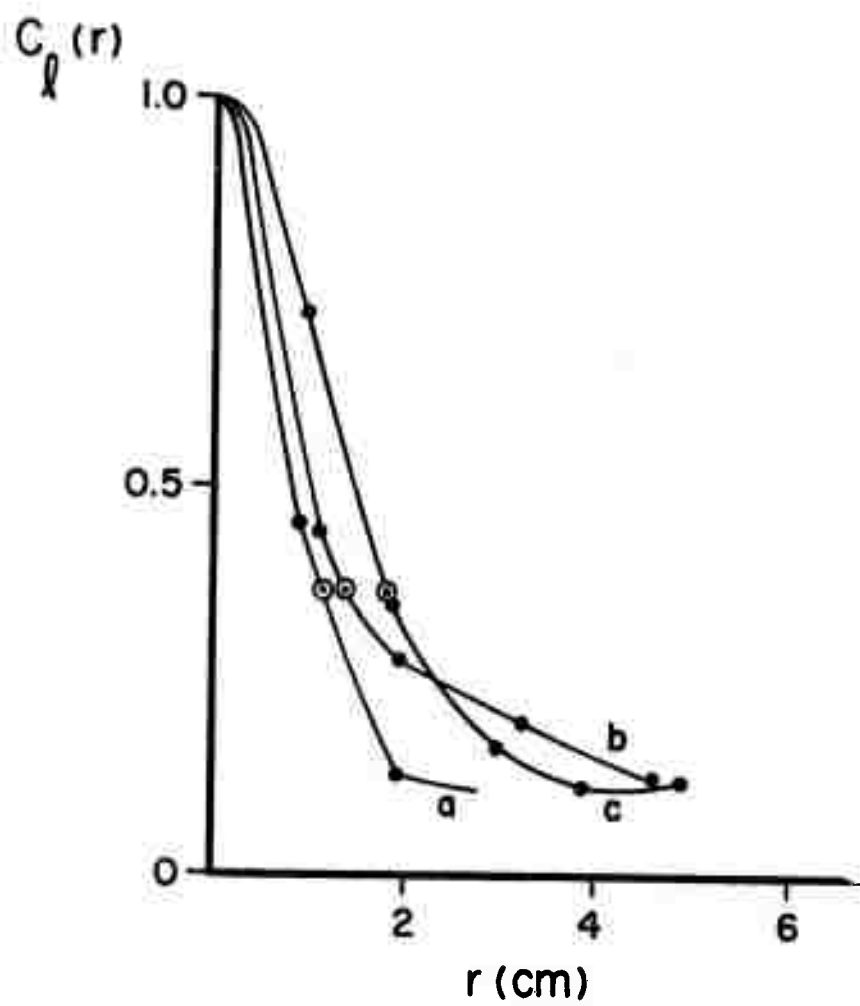


FIGURE 9

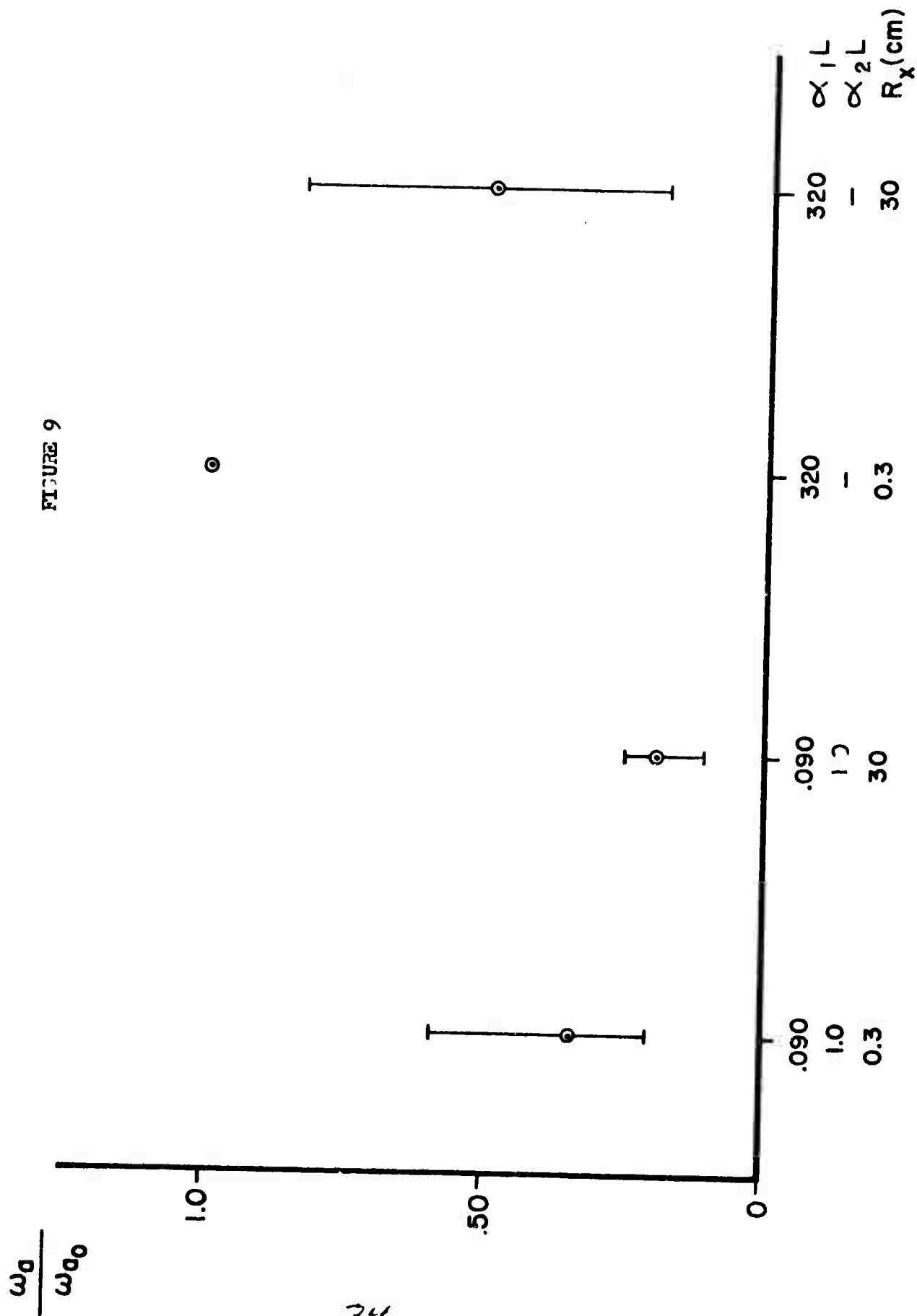


FIGURE 10

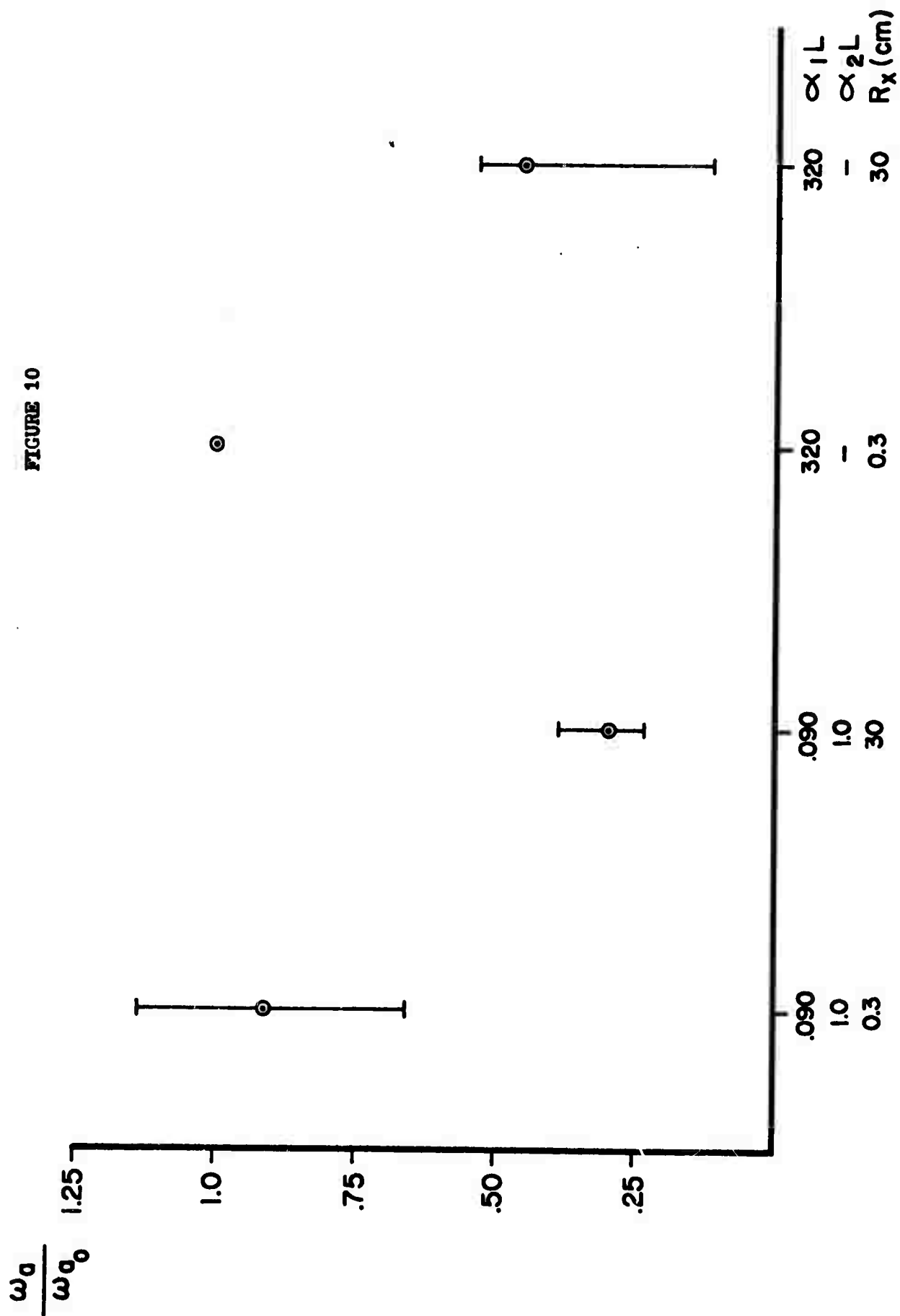


FIGURE 11

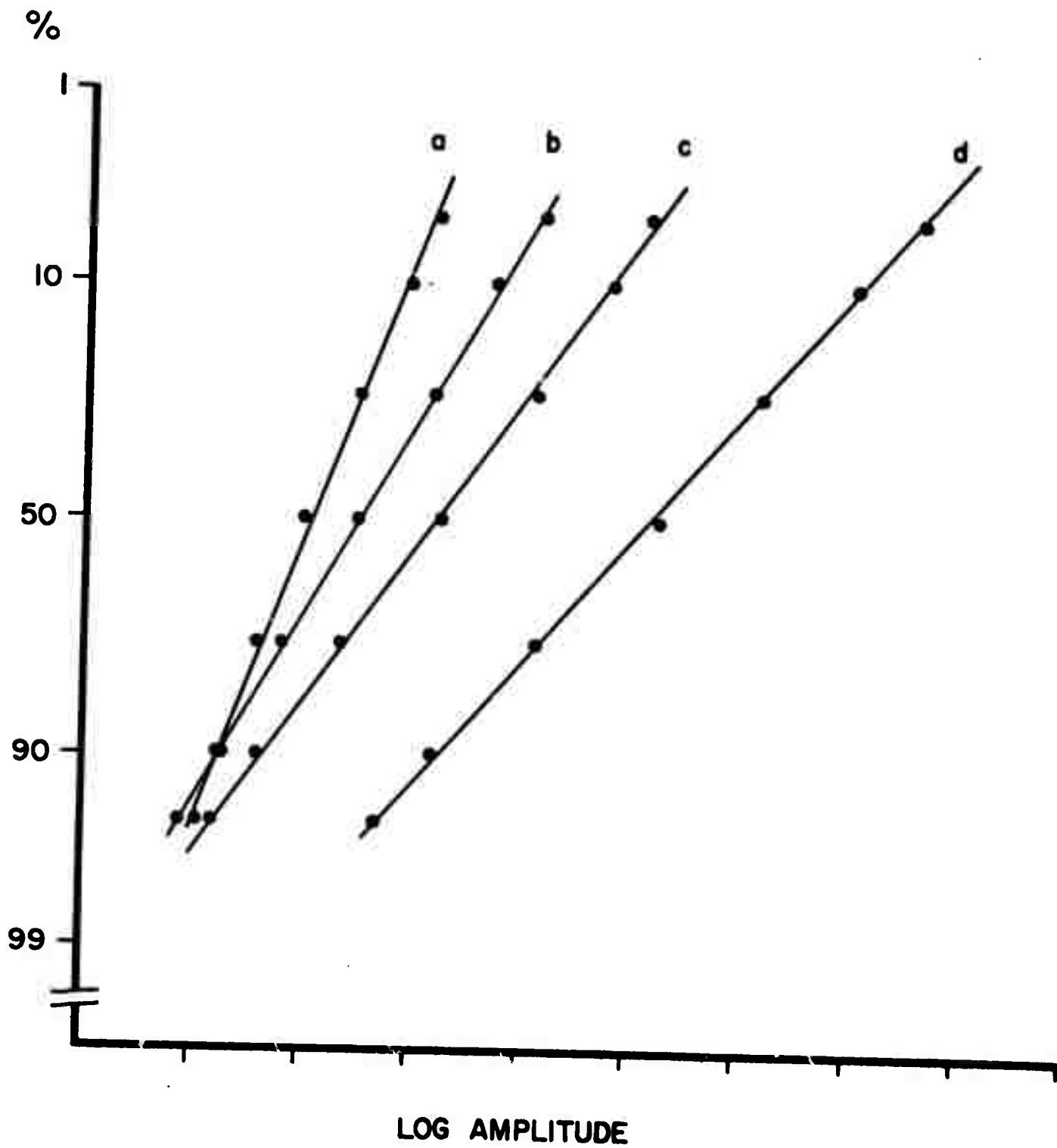


FIGURE 12

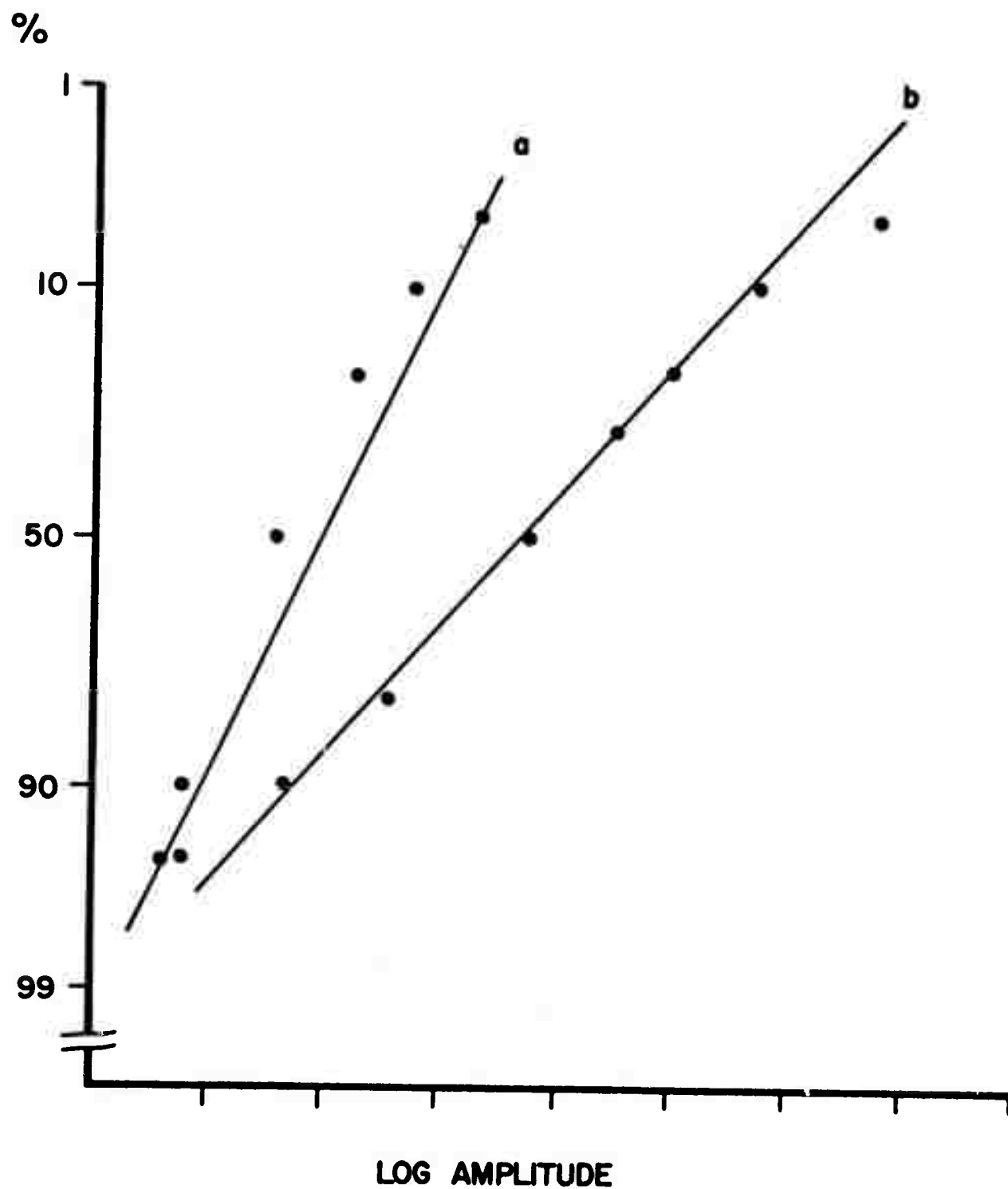


FIGURE 13

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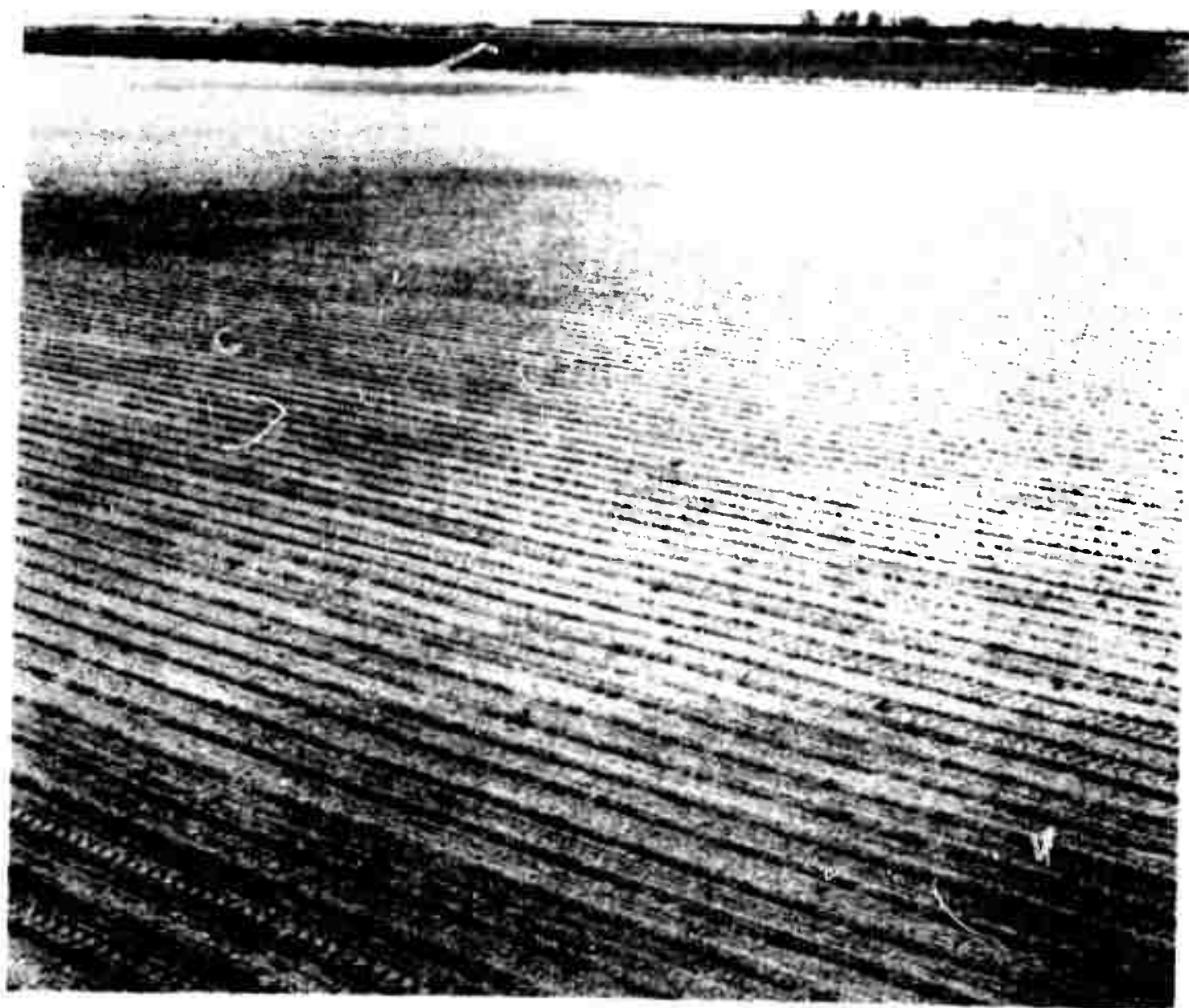


FIGURE 14

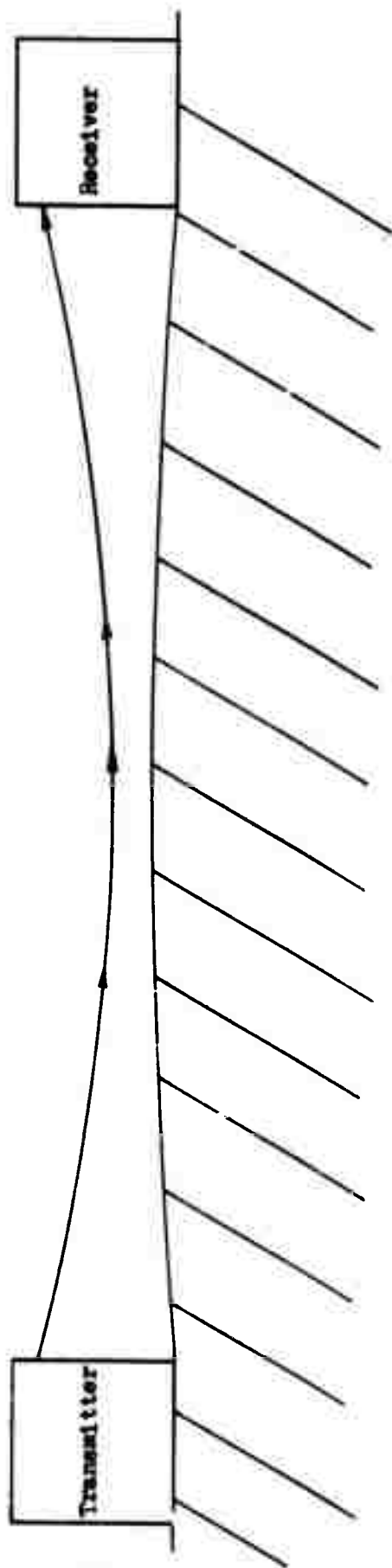


FIGURE 15

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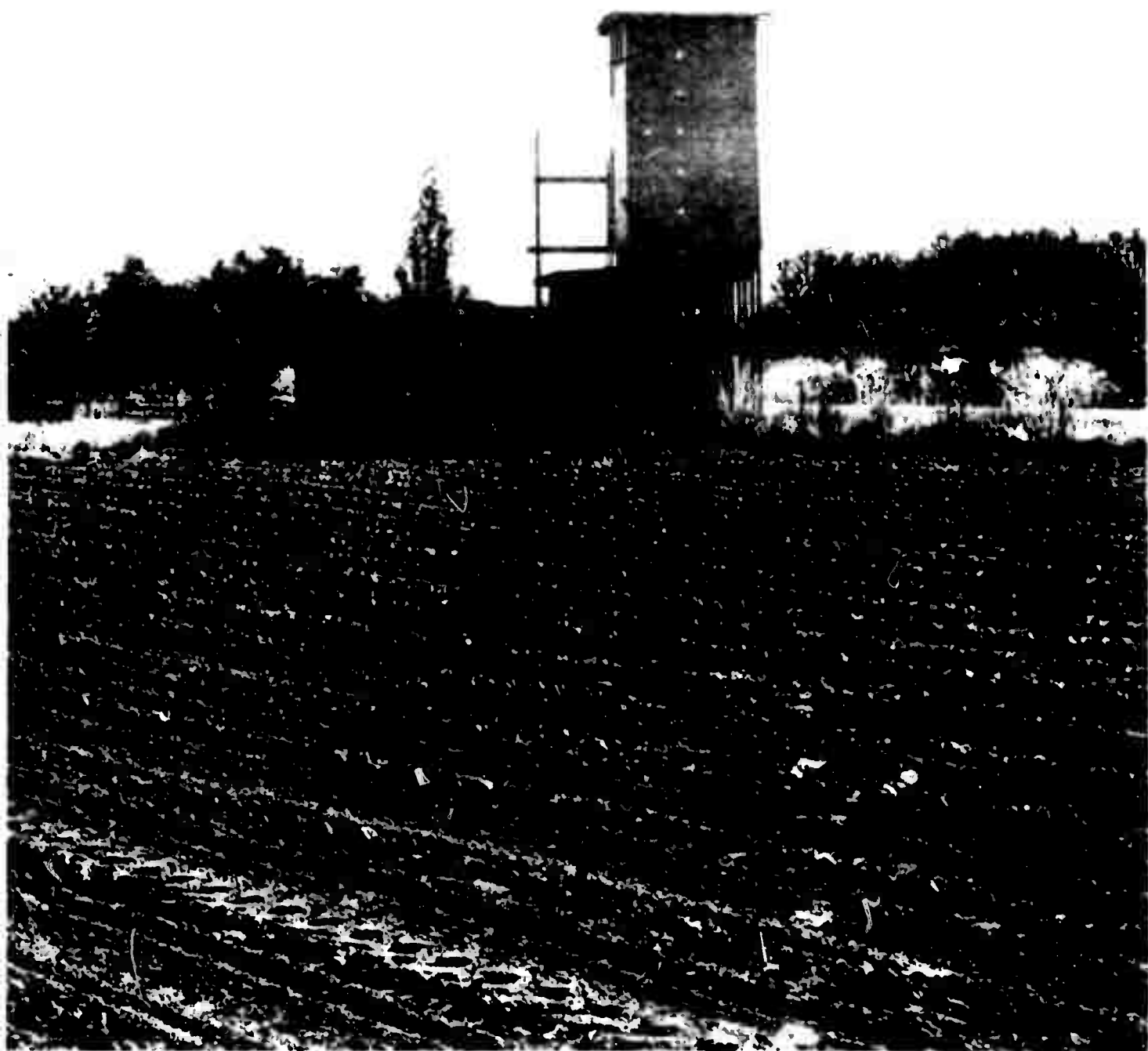
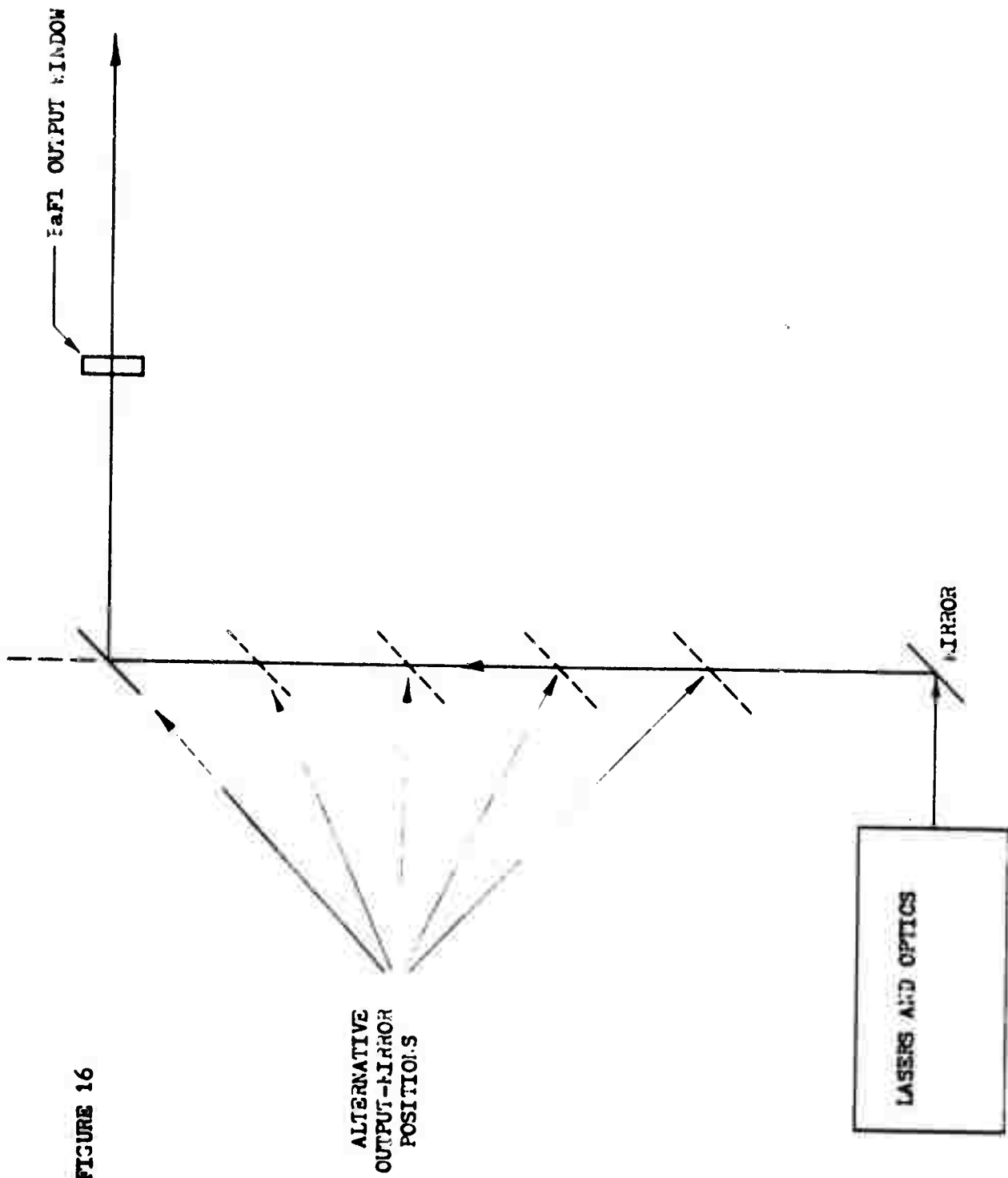
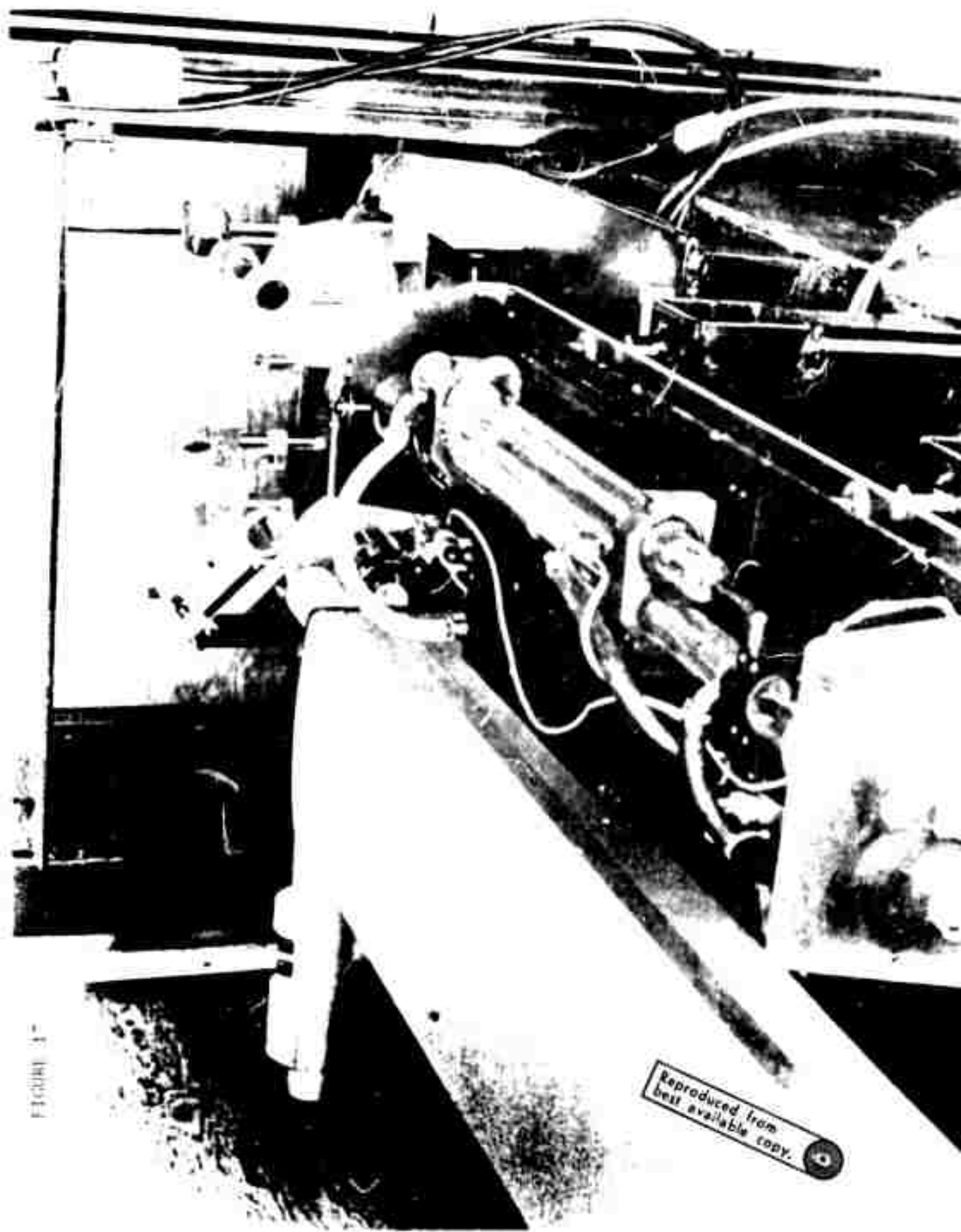


FIGURE 16





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FIGURE 18

